

Back to the Future: Long-range U. S. Energy Price and Quantity Projections in Retrospect

Alan H. Sanstad* and Jonathan G. Koomey
Lawrence Berkeley National Laboratory

John A. “Skip” Laitner
U. S. Environmental Protection Agency

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Introduction and Overview

Prior to the first oil shock of the 1970s, long-run projections of U. S. aggregate energy use tended to extrapolate the first quarter-century post-war pattern of steadily increasing demand (Sweeney 1984). The oil shocks, of course, demonstrated both that energy prices could change substantially and that the economy would be responsive to such changes. For this reason among others, projections of year 2000 demand from that era have proven to be systematically too high, in some cases by a factor of approximately two. It is also well-known that in the aftermath of the oil shocks, long-run oil prices tended to be overestimated by forecasters. Such factors as the instability of the OPEC cartel and unanticipated technological progress in extraction prevented the anticipated price increases (Adelman 1993, Krautkraemer 1998).

*Corresponding author: Mailstop 90-4000, Lawrence Berkeley National Laboratory, #1 Cyclotron Rd., Berkeley, CA 94720. Lawrence Berkeley National Laboratory’s contribution to this work was supported by the Office of Atmospheric Programs, U. S. Environmental Protection Agency. We would like to thank Julia Hutchins and Ronald Earley of the U. S. Energy Information Administration for their invaluable help in understanding the EIA’s energy price and expenditure estimation methods, and Don Hanson and Steve DeCanio for advice on an earlier draft. Finally, we thank John Weyant and Hill Huntington for their comments and for the opportunity to present the work described in this paper at meetings of the Energy Modeling Forum. Prepared for the U. S. Department of Energy under Contract No. DE-AC03-76SF00098.

The sources of errors in oil price forecasting and their relationship to demand assumptions have been previously analyzed by Hogan (1993) and Huntington (1994), among others. In this paper, we retrospectively examine a broader pattern that emerged in the aftermath of the oil shocks: long-range U. S. energy forecasts that arrived at relatively *low* demand growth estimates (by historical standards) in conjunction with relatively *high* price estimates for a variety of energy resources. We focus on five long-range energy studies (of the U. S.) conducted independently in the early 1980s. Four of these studies were reviewed in conjunction with the U. S. Department of Energy’s National Energy Policy Plan of 1983 (NEPP83), and the fifth conducted as part of the analysis for that plan. The forecast horizon for each of these studies was the year 2000 or later, so that we can now compare their projections with the actual course of events since the early 1980s. Indeed, the present paper can be considered a follow-up to NEPP 83, asking as it were, “where are they now”?

We find that these studies implicitly embodied a view of long-run energy-economy interactions that turned out *ex post* to have omitted a fundamental trend of the last two decades. In particular, from the early 1980s through the late 1990s the U. S. economy saw both relatively moderate growth in energy demand *and* declining real energy prices, a pattern unanticipated twenty years ago. In other words, the year 2000 consumption level projected then has been approximately reached with much weaker price signals than were expected. Even with the rapid price increases for several fuels in the year 2000, real prices remained below their early 1980s levels. The implication is that, in the aggregate, the economy has become much more energy-efficient than was foreseen.

The apparent explanation of this occurrence is some combination of sectoral and aggregate technological change, compositional shifts in the economy, and engineering-level energy-efficiency improvements - i.e., non-price or “autonomous” factors or trends in aggregate energy intensity. The early-to mid-1990s discussion saw an active discussion in the modeling community of the magnitude of such autonomous trends and their significance for long-run energy modeling (Hogan and Jorgenson 1991, Manne and Richels 1992, EMF 1996). Most previous work on this topic, however, focused on the empirical interpretation of the historical record and how it could be applied prospectively to model calibration. By contrast, this paper is a retrospective examination of how assumptions regarding autonomous energy-saving trends affected the accuracy of specific model-based projections.

Aggregate energy-economy relations of the type of interest here are often

discussed in terms of trends in $\frac{E}{GDP}$, the ratio of energy consumption to gross domestic product. The key limitation of this statistic is that it fails to distinguish the effects of price changes from those of other factors. Overcoming this drawback requires an explicit model of the relations among energy prices and quantities, GDP, and other factors that reduce aggregate energy intensity independent of price changes. Accordingly, we apply in this paper a well-known model devised by Hogan and Manne over two decades ago, extending this model to include a form of “autonomous energy efficiency index” or “AEEI” (EMF 1996). This will allow us to approximately quantify the assumptions in the studies we examine, and to compare their projections with the actual path of the economy since the early 1980s. We numerically estimate the degree to which the early-1980s studies underestimated the autonomous trend. To illustrate the policy significance of this type of underestimation, we show that it would have resulted in analysts of that era *overestimating* the economic cost of a prospective carbon or energy tax in the (then future) year 2000.

The latter calculation, in particular, provides what amounts to a cautionary note regarding *current* model-based estimates of carbon abatement costs. That such estimates are subject to unavoidable forecasting error is uncontroversial. However, correctly representing - or not - recent and current relationships among energy prices, demands, and autonomous factors is a fundamentally different matter than anticipating - or not - events that are arguably unforeseeable, such as the oil shocks or the discovery of substantial new petroleum reserves. It is instead matter of how economic and technological relationships underlying energy production and use should be represented. Energy-economic simulation models have in key respects evolved substantially since the the two-decade-old vintage considered here, and the character and significance of such influences on aggregate long-run trends have been actively debated in the modeling community. But these factors - especially technological change - remain controversial, and it is not clear how much fundamental progress in measuring them and representing them in simulation models has been made in the past two decades. This uncertainty has important implications in the analysis of policies to address global climate change, the primary current application of the models. Disagreement over the rate and character of energy-saving technological change, for example, was a key reason for the failure of the U.S. government’s initial attempt to formulate a quantitative national climate policy in the 1990s. Our results are, minimally, a reminder that the constellation of issues surrounding the “AEEI” remain pertinent to such efforts, and maximally provide evidence

that these issues deserve renewed attention from modelers.

The paper is organized as follows. We begin by documenting the early 1980s projections of aggregate energy demand, prices for various fuels, and economic growth along with summary statistics on the errors in these projections. Next, we review the Hogan-Manne model and summarize our elaboration of it (with technical details presented in the Appendix). We then turn to a series of retrospective applications of this model, first inferring what autonomous trends were implicit in the projections, and then estimating with perfect hindsight what trends have actually been realized in the economy, both over the past twenty years and in the longer period from 1970 to the present. In the course of presenting these estimates, we address potential objections to our results. We then present the result noted above, how the early 1980s models would have apparently overestimated the economic costs of a then-future energy tax in the year 2000. Finally, we relate our analysis to recent trends in the American economy involving the diffusion of information technology, and conclude with a general discussion.

The Price-Quantity “Gap” in Long-run Forecasts

Through the mid 1970s, long-range forecasts tended to conclude that the post-war pattern of steadily rising energy demand would continue into the foreseeable future. For example, the U. S. Atomic Energy Commission projected in 1973 that aggregate U.S. energy consumption in the year 2000 would be on the order of 180 quads (USAEC 1973). In another example, in 1974 the Federal Energy Administration developed a base case forecast of more than 140 quads in the year 2000; this study suggested that even with emphasis on promoting energy efficiency, year 2000 consumption would be 120 quads (USFEA 1974).

The lesson of the 1970s – that the economy was responsive to energy prices, and that these prices were subject to change – was clearly reflected in energy studies as that decade progressed. By the early 1980s, long-range forecasts of U. S. demand had fallen substantially. This was reflected in the five studies we focus on here, which are listed in Table 1.

Table 1: Early 1980s U. S. Energy Projections		
<i>Sponsor</i>	<i>Title</i>	<i>Date Released</i>
U. S. DOE	<i>Energy Projections to the Year 2010 (“NEPP 83”)</i>	July 1983
American Gas Association (AGA)	<i>TERA Analysis</i>	February 1983
Gas Research Institute (GRI)	<i>1982 GRI Baseline Projection of U. S. Energy Supply and Demand, 1981-2000</i>	October 1982
Data Resources, Inc. (DRI)	<i>Energy Review</i>	Spring 1983
Applied Energy Services, Inc. (AES)	<i>Least-Cost Update</i>	February 1983

These studies employed a variety of methods, including macroeconomic, linear programming, and energy system modeling techniques. Their conclusions

were generally consistent, however, and moreover have proven to be fairly accurate in anticipating year 2000 consumption. These projections are displayed in Table 2; note that year 2000 aggregate U. S. consumption is estimated by the Energy Information Administration to have been 98.5 quads (USEIA 2001a).

Table 2: Projections of Aggregate U. S. Energy Demand in the Year 2000		
<i>Study</i>	<i>Projected Demand (Quads)</i>	<i>% Error from Actual</i>
NEPP 83	93.4	-5.2
AGA	95.8	-2.7
GRI	96.4	-2.1
DRI	92.3	-6.3
AES	89.6	-9.0
Median	93.4	-5.2

The starting point for the analysis in this paper is the observation that these quantity forecasts were made under corresponding projections of considerably higher energy prices than have actually been realized as well as underestimates of year 2000 GDP. Tables 3A and 3B summarize the price projections in these studies, and compare them with current estimates of actual prices for the year 2000, while Table 3C displays the projected and actual GDP. (Our estimate for 2000 GDP is \$9224 Billion (USDOC 2001); actual energy prices are taken from the August 2001 *Short-term Energy Outlook* (USEIA 2001b) and from the *Annual Energy Outlook 2001* (USEIA 2000a).)

Table 3A: Projections of Primary Fuel Prices, and Errors (Prices in 1996 dollars)				
<i>Fuel</i>	<i>1982 Price</i>	<i>Median Projection of 2000 Price</i>	<i>Actual 2000 Price</i>	<i>Median % Er from Actua</i>
World Oil	\$50.70/bbl	\$77.22/bbl	\$26.01/bbl	197
Wellhead Gas	\$3.56/million btu	\$9.95/million btu	\$3.10/million btu	221
Minemouth Coal	\$1.99/million btu	\$2.92/million btu	\$0.73/million btu	296

Table 3B: Projections of Delivered Energy Prices, and Errors (Prices in 1996 dollars per million btu)					
<i>Sector</i>	<i>Fuel</i>	<i>1982 Price</i>	<i>Median Projection of 2000 Price</i>	<i>Actual 2000 Price</i>	<i>Median % Error from Actual</i>
Residential/ Commercial	Natural Gas	\$7.55	\$12.91	\$5.31	143
	Electricity	30.35	32.09	20.55	56
Industrial	Natural Gas	\$5.43	\$11.88	\$2.80	324
	Electricity	21.90	28.52	12.66	125
	Residual Fuel Oil	7.40	12.14	3.21	278
Transportation	Gasoline	\$15.46	\$23.25	\$10.19	128

Table 3C: Projections of U. S. GDP in the Year 2000 (billions of 1996 dollars)		
<i>Study</i>	<i>Projected GDP</i>	<i>% Error from Actual</i>
NEPP 83	\$8085.47	-12.3
AGA	8197.42	-11.1
GRI	7777.64	-15.7
DRI	8101.76	-12.2
AES	7808.29	-15.3
Median	8085.47	-12.3

Two observations are in order before we turn to analyzing the assumptions implicit in these projections. First, as noted in the Introduction, the projections of world oil prices in these studies were by no means idiosyncratic. For example, nineteen forecasts of year 2000 world oil prices reported by the International Energy Workshop in 1983 had a median of \$61 per barrel (in 1982 U.S. dollars), for a median error of 251% (Beltramo and Manne 1983). Second, we note that these projections were also not unique in underestimating U.S. economic growth in the 1990s. To the extent that, in the models used, economic growth entered as an exogenous or partially exogenous driver of energy demand, we would conjecture that simulations using those models in which actual economic growth was projected would have raised energy demand estimates to or somewhat above the actual year 2000 level under the given price assumptions. If so, then the energy price-quantity “gap” in these projections would in retrospect be even more striking.

The Elephant and the Rabbit Redux

Our particular aim is to understand the implicit interaction in these projections between assumptions regarding the magnitude of price-induced substitution possibilities on the one hand and the importance of non-price or “autonomous” factors on the other. The energy-modeling literature of the late 1970s

and early 1980s reveals a focus on the question of substitution in general and the estimation of various demand elasticities in particular (for example, EMF 1977, Hogan et al 1981, Sweeney 1984.). In a now-classic paper from this literature, Hogan and Manne (1977) devised a simple but very useful framework for analyzing aggregate energy trends in the economy. (This framework has turned out to be something of a prototype for a number of subsequently-developed large-scale simulation models.) Their paper was a centerpiece of the first report of Stanford University’s Energy Modeling Forum, focused on the phenomenon of substitution between energy and other factors, and discussed how the aggregate elasticity of substitution between energy and other factors influenced the costs of reducing energy consumption in the long run. With one variation, the Hogan and Manne model will allow us to analyze the studies summarized in the previous section. We first describe this theoretical variation, and then how we applied the resulting model to the five 1980s studies. We summarize the results here; details are presented in the Appendix.

In the Hogan-Manne model, at any time t there are two inputs to an aggregate production function, energy E_t and a composite of all other goods R_t , with prices P_{E_t} and P_{R_t} , respectively. The gross output Y_t of the non-energy sector is assumed to have a constant (over time) price of 1, and is measured in the same units as GDP. Energy is assumed to be an intermediate input. Thus, the following accounting identities hold:

$$\begin{aligned} Y_t &= P_{E_t} E_t + P_{R_t} R_t \\ &= P_{E_t} E_t + GDP_t. \end{aligned} \tag{1}$$

These inputs and output are related by a constant-elasticity-of-substitution (CES) production function:

$$Y_t = \left(a^{\frac{1}{\sigma}} E_t^{\frac{\sigma-1}{\sigma}} + b^{\frac{1}{\sigma}} R_t^{\frac{\sigma-1}{\sigma}} \right)^{\frac{\sigma}{\sigma-1}}, \tag{2}$$

where a and b are parameters and σ is the elasticity of substitution between E and R . (The parameter σ is also approximately equal to the price elasticity of energy demand.) As the absence of time subscripts implies, Hogan and Manne assumed both a and b to be fixed through time, so that changes in the mix of E_t and R_t or in the energy intensity $\frac{E_t}{Y_t}$ could result only from changes in relative prices. In other words, neither technological change in particular nor other non-

price-induced influences on energy-intensity in general are directly represented in the model.

To amend the model to allow for exogenous or autonomous energy-intensity reduction, we re-write it in a slightly more general form,

$$Y_t = \left(a_t^{\frac{1}{\sigma}} E_t^{\frac{\sigma-1}{\sigma}} + b_t^{\frac{1}{\sigma}} R_t^{\frac{\sigma-1}{\sigma}} \right)^{\frac{\sigma}{\sigma-1}}, \quad (3)$$

in which the parameters a_t and b_t are also time-dependent. When either of these parameters varies with time, the mix of inputs into production - and therefore their associated intensities - will in general also vary with time, even in the absence of changes in relative prices. This amounts to a definition of “autonomous” or “exogenous” technological change. As shown in the Appendix, with this formulation the autonomous trend is given by

$$\frac{\partial \ln \left(\frac{E_t}{Y_t} \right)}{\partial t} = \frac{\dot{a}}{a}. \quad (4)$$

This quantity is an index - an “AEEI” - for the change in energy intensity E_t/Y_t over time holding prices fixed.

Under standard assumptions regarding behavior and the economic environment (i.e., competitive equilibrium, profit-maximization on the part of the representative firm, and instantaneous adjustment of the equilibrium to price changes), the model defined by Equations 1 and 3 can be calibrated to actual values over time of Y_t , E_t and R_t given energy prices and values for GDP and a value for σ (which is assumed to be constant over time). Such a calibration yields values for a_t at different points, so that the autonomous trend defined in Equation 4 can then be calculated. The simplest such calibration, which we will apply, requires these various quantities only for an initial and a terminal year. The autonomous trend is then obtained as an average rate between these two end points.

Our first aim here is to estimate what “average” (across studies) autonomous trend was implicit in the year 2000 projections reported in the five early-1980s studies. To apply the just-described calibration procedure for this purpose, we first extract a “median” or representative study from the five. More precisely, we start with the common values of the prices and quantities in the base year 1982. We then calculate the *median* projected year 2000 prices and quantities from the five forecasts to arrive at a single set of year 2000 prices and quantities. With these data, and a value of σ , the model can be calibrated so that both the 1982

and the median projected 2000 quantities E_t of energy demanded are solutions to the model's first-order conditions in the two years given the 1982 energy price and the median forecasted year 2000 energy price. This calibration yields the values a_{1982} and a_{2000} of the parameter a , from which the average value (over the period 1982-2000) of the autonomous trend defined in Equation 4 can be derived. This gives, again as a function of σ , an approximation to the implicit autonomous trend in the "median" forecast. (The reason that a_t , and therefore the autonomous trend, depend on σ is made clear in the derivation presented in the Appendix.)

The missing element here is exactly what value of σ should be used to carry out these calculations. The documentation available to us does not report this elasticity for any of the five studies. For example, the NEPP83 technical report, which provides an extensive description of both methods and results, discusses conceptually the importance of this substitution parameter but does not report its actual value in that study. Beyond this, however, in addition to incomplete source materials, it is also the case that the models actually used in the studies - being considerably more detailed than the simple one here - may not have had single parameters corresponding to the aggregate substitution elasticity σ . Rather, the assumed substitution elasticities would have been implicit in the overall behavior of the models, and would have required a series of simulations of each model to determine. We therefore do not use a single value of σ but instead refer to the literature of the early 1980s to obtain a range of plausible values for this parameter that emerged from research at that time (Hogan et al, 1981), and use the range 0.1 to 0.7, which was also the range considered by Hogan and Manne.¹

Table 4 displays the results of a set of calibrations using the method described above, as a function of the assumed value of σ :

¹We could have instead calibrated the results of *each* study given different values of σ rather than extract a "median" forecast. The key reason for not undertaking this larger set of calculations is that the qualitative point we are making would not have been affected given that the various studies' price and quantity projections were reasonably close together. In addition, there is in fact a several-dimensional continuum of parameter combinations that could be determined from this type of calibration. For example, we could have allowed σ also to vary with time, so that the underlying substitution possibilities changed from 1982 to 2000. This would be appropriate in a more exhaustive study, but is unnecessary to convey the simpler point we are making here.

Table 4: Autonomous trend in $\frac{E_t}{Y_t}$ as a function of substitution elasticity - median projection, 1982-2000	
Value of σ	Implied average annual % autonomous change in $\frac{E_t}{Y_t}$
0.1	-1.27
0.2	-1.09
0.3	-0.9
0.4	-0.72
0.5	-0.54
0.6	-0.35
0.7	-0.17

EMF13 (1996) and Weyant (1993) report that analysts have generally applied a value of the autonomous trend in the range -0.5% to -1.0%. Our results here bracket this range for “middle” values of σ . The story told by these numbers is straightforward. The higher the substitution elasticity and the corresponding price elasticity of demand, the more the economy would have been expected to respond to the anticipated general increase in energy prices. Thus, at higher elasticity values, and all else being equal, less of a non-price or autonomous effect would be required to supplement the direct substitution effect in order to meet the anticipated consumption levels. Since, in this simple model, all else is equal by definition and we have defined the change in the parameter a as the only alternative mechanism for reducing energy demand, this supplemental effect is captured entirely by the resulting autonomous trend in $\frac{E_t}{Y_t}$.

Applying 20-20 Hindsight

We now turn to the next logical question: what parameterization of this model would have resulted in an accurate prediction, in 1982, of both price and quantity trends through the year 2000? Put differently, what parameterization is required to calibrate the model to *actual* price and quantity changes from 1982 to 2000, and specifically what average rate of autonomous energy intensity reduction is implied? To answer this question, we use the same (actual) 1982 data but, instead of using median quantities from the five studies, as above, we use year 2000 data on E_t , GDP, and energy prices (using certain approximations described in the Appendix). As before the calculations are a function of σ ; the results of these “perfect hindsight” calibrations are displayed in the following table.

Table 5: Autonomous trend in $\frac{E}{Y}$ as a function of substitution elasticity, “perfect hindsight” case, 1982-2000	
Value of σ	Implied average annual % autonomous change in $\frac{E}{Y}$
0.1	-1.7
0.2	-1.9
0.3	-2.1
0.4	-2.3
0.5	-2.5
0.6	-2.7
0.7	-2.9

We first observe that, overall, this exercise gives a rather different picture of the importance of the autonomous trend - in absolute value, the *lowest* rate is now higher than the *highest* rate among the “median projection” calibrations. Correctly accounting for realized trends over the past two decades requires, in this model, a considerably higher rate of autonomous intensity reduction than was assumed in the early 1980s projections. The pattern of parameter values obtained in these calibrations inverts that of the previous exercise. With a lower elasticity, the economy would respond less to a reduction in real energy prices, so that relatively less of an autonomous trend would be required to “prevent” an even greater increase in consumption. As the elasticity increases, the underlying substitution response to a drop in prices becomes stronger, so that a higher rate of non-price-induced reduction in energy demand - represented here as the autonomous trend - is required to “prevent” a greater decrease in consumption than what has actually been observed.

Caveats and Discussion I

By econometric standards, these estimates of the “AEEI” are no more than “back-of-the-envelope” calculations. As discussed at length by Hogan and Jorgenson (1991), rigorously estimating a plausible economy-wide “AEEI” through aggregation from the sectoral level is a matter of considerable delicacy. With respect to evaluating the early-1980s studies, however, we would argue that our results strongly suggest that the autonomous trend *however it is defined and measured* was underestimated in these studies. We draw some further implications of this finding in a succeeding section.

Before proceeding to this, it is worth further applying our simple method, its shortcomings notwithstanding. Our estimates of the “perfect hindsight” autonomous trend over the past two decades are much higher than those that

have apparently been used by the modeling community to parameterize large-scale models for simulations over much longer (future) time periods (Weyant 1993, EMF 1996). One reason for this is the use of 1982 as a base year: this was arguably a “disequilibrium” year, with the economy continuing to adjust to the then-most recent oil price shocks. This effect is not accounted for in our method, which assumes instantaneous price adjustment. In addition, 1982 was a “trough” year in the business cycle, which would also tend to yield higher-than-otherwise estimates.

1982 is, however, arbitrary outside this context, that is, for analyzing studies undertaken twenty years ago. For this reason, we next report results of a similar set of calibrations for different historical periods.

Varying the Base and Terminal Years

The actual U. S. $\frac{E}{GDP}$ trend has varied considerably since World War II. From 1970-97, for example, the annual average change in $\frac{E}{GDP}$ was -1.5%, while during the decade 1976-86 - as the oil price shocks worked their way through the system - it was -2.9% (Kooimey et al 1998). To put the above calculations into a larger context, we also carried out “perfect hindsight” calculations for several historical time periods. In each case, we use as a base year 1970, the first year for which the Energy Information Administration’s long-term price index is available. (This is the index reported in the *State Energy Price and Expenditure Report* and the *Annual Energy Review* series; see Appendix.) This allows us to apply our calibration method without needing to introduce further approximations to obtain price estimates for earlier years.

The first period is 1970-82. These calculations, presented in Table 6, illustrate the trends in the decade immediately preceding the early-1980s projections. The results display an interesting contrast to the previous calculations: in this period, for most values of σ , the autonomous trend was *energy-using*, in the sense that the non-price factors resulted in *increasing* energy intensity (Hogan and Jorgenson, 1991). Comparing with Table 4, these estimates indicate that those projections, despite having turned out to underestimate autonomous influences *ex post*, were at the time actually optimistic regarding the possibilities for such influences in then-future years.

Table 6: Autonomous trend in $\frac{E}{Y}$ as a function of substitution elasticity, “perfect hindsight” case, 1970-82	
Value of σ	Implied average annual % autonomous change in $\frac{E}{Y}$
0.1	-1.66
0.2	-1.02
0.3	-0.39
0.4	+0.26
0.5	+0.9
0.6	+1.55
0.7	+2.2

Our next set of calculations, presented in Table 7 gives the results for the three-decade period 1970-2000. Over this longer period, the autonomous trend displays the same qualitative pattern as the median forecast case for 1982-2000: the trend is higher at lower values of σ because the average price increased over this period. In addition, the estimates for the trend are uniformly lower than those in the perfect hindsight case for 1982-2000. On the other hand, they exceed the conventionally accepted range of -0.5% to -1.0%.

Table 7: Autonomous trend in $\frac{E}{Y}$ as a function of substitution elasticity, “perfect hindsight” case, 1970-2000	
Value of σ	Implied average annual % autonomous change in $\frac{E}{Y}$
0.1	-1.7
0.2	-1.57
0.3	-1.44
0.4	-1.3
0.5	-1.17
0.6	-1.0
0.7	-0.9

Our final set of AEEI calculations are for the period 1970-1997, and are displayed in Table 8. The reason for choosing 1997 is two-fold. First, it is the last year for which the EIA price index is currently available, so that no price-related approximations are needed in this case. Second, and more important, it allows for applying our calibration method to an historical epoch that is “long” but does not encompass the substantial price increases for several fuels that occurred in 1998-2000. If these price increases turn out to be due to short-run factors rather than a signal of the onset of long-run scarcity, then these calculations are likely to provide a better estimate - within, of course, the limits of our simple method - of the current direction of the long-run trend in autonomous factors.

Table 8: Autonomous trend in $\frac{E}{Y}$ as a function of substitution elasticity, “perfect hindsight” case, 1970-1997	
Value of σ	Implied average annual % autonomous change in $\frac{E}{Y}$
0.1	-1.65
0.2	-1.57
0.3	-1.49
0.4	-1.41
0.5	-1.33
0.6	-1.25
0.7	-0.17

These estimates, while again much lower than those for 1982-2000, are (except for the lowest values of σ) somewhat greater than those for 1970-2000 and comfortably greater than the “conventional wisdom” as noted previously.

Caveats and Discussion II

Because of the elementary nature of these calculations, we do not propose that they supplant the standard estimates of the “AEEI.” On the other hand, given the existing consensus around an AEEI between -0.5% and -1.0%, we view them as strongly suggesting that more carefully estimating the magnitude of long-term autonomous influences in the U. S. energy economy warrants renewed attention. As noted above, any bias due to failure to account for “disequilibrium” (i.e., adjustment) effects is at least somewhat mitigated by focusing on base and terminal years at which prices were relatively stable. A second question is the assumed mechanism for relating price to demand changes, which we model here in the simplest possible way. Dargay and Gately (1995), for example, find econometric evidence of asymmetric demand responses to oil price changes, thereby accounting in part for the observed post-early-1980s “hysteresis” effect of demand not rebounding in the face of falling prices. Omitting this type of mechanism results in an upward bias in measurements of autonomous energy-saving trends. There is also emerging evidence that the general class of model we apply in this paper, in which the sole mechanisms for changes in energy intensity are substitution and autonomous trends, may be mis-specified because it defines away the direct influence of price changes on technological improvement. Both Newell et al.(1999) and Popp (2001) find evidence of sizable such “endogenous” or “induced” effects. The existence of such effects suggests a different explanation of the hysteresis observed over the past two decades: to the extent that the rapid price increases in the 1970s and early 1980s resulted in energy-saving technological *change* in addition to energy-saving *substitution*,

one would expect that demand would, indeed, fail to fully rebound once prices began their long period of decline.

Such research suggests several paths for more rigorous empirical scrutiny of the AEEI “problem,” and there are no doubt others. In the specific context of energy-economic simulation modeling as currently practiced, however, these methodological qualifications to our results carry somewhat less weight. The reason is that virtually all such models, while containing much more detail, nonetheless allow for only the two mechanisms represented in our simple calibration: symmetric substitution and autonomous trends. Thus, for example, asymmetric demand response may very well help to explain U. S. energy trends over the past twenty years, and including this type of response, *ceteris paribus*, may result in lower values for the AEEI. This does *not*, however, constitute evidence that such lower AEEI estimates are thereby justified in standard energy-economic simulation models. It is instead evidence that these models are mis-specified insofar as they omit asymmetric response. For purposes of evaluating, and possibly improving upon, the standard simulation models, the appropriate extension of the simple calibration we report here is to apply more sophisticated techniques to larger datasets while maintaining the assumptions that are built into these models. From this perspective, our results, while elementary, suggest that such an effort is warranted.

Why it (Would Have) Mattered

The most common current use of energy-economic simulation models is to estimate the economic costs of large-scale carbon abatement. Such analyses are generally one of two types: cost-benefit studies, in which optimal abatement rates, and thus carbon or energy taxes, are estimated in relation to projected damages from global climate change, and scenario-based cost studies, in which either a given level of abatement or of tax is assumed and the economic costs derived accordingly. Of the latter, a reasonably common benchmark is \$50 (US) per ton of carbon, currently corresponding to a roughly 15% increase in the average price of energy.

This sort of calculation was not part of the studies we are examining here. However, it is instructive to consider in hindsight how the autonomous “effect” we have found would have influenced the results of such an estimate two decades ago. In other words, suppose that policy-makers in 1982 wished to project the effects of a 15% rise in the price of energy in the year 2000. Table 9 displays the results of using both the “median” and the “perfect hindsight” models calibrated above to estimate the GDP losses incurred by such a price increase, again as

a function of σ . Note that in this table, for each value of σ , the “median” and “perfect hindsight” GDP losses are with respect to the year 2000 GDP as estimated in the median and perfect hindsight calibrations, respectively.

Table 9: GDP impacts of 15% rise in energy price, year 2000		
Value of σ	Model	GDP Loss as % of Baseline GDP
0.1	Median	1.24
	Perfect hindsight	0.68
0.2	Median	1.08
	Perfect hindsight	0.59
0.3	Median	0.91
	Perfect hindsight	0.49
0.4	Median	0.75
	Perfect hindsight	0.40
0.5	Median	0.59
	Perfect hindsight	0.31
0.6	Median	0.43
	Perfect hindsight	0.22
0.7	Median	0.26
	Perfect hindsight	0.13

As shown in the table, the difference between the median projected (implicit) rate of autonomous change, and that which was actually realized, results in a substantial difference in estimated GDP impacts - a nearly 100% overestimate of the percentage loss from baseline GDP for each value of the elasticity. Put differently, a policy-maker in 1982 applying our inferred “median” model and, we surmise, any or all of the models used in the five studies, would have overestimated the economic cost of a 15% energy tax in 2000 by a factor of nearly two.²

Relation to Current Events

²As is standard in this form of analysis, the Hogan and Manne model assumes that policy-induced deviations from the untaxed equilibrium necessarily entail GDP losses. Alternative analyses, however, suggest otherwise (see, for example, Laitner and Hanson, 2000; Bernow et al, 1998). A forthcoming paper will explore formulations in which, when new energy-saving investments increase the marginal product of capital and labor, GDP can actually increase so long as transaction costs are relatively small.

Absent a crystal ball, we will look forward to undertaking a sequel to this analysis circa 2020, when history will have revealed the accuracy of current projections and possibly, should large-scale carbon abatement be undertaken in the coming decades, will have provided an actual experiment to evaluate in place of this hypothetical GDP loss calculation. At present, however, it is of interest to speculate, if nothing else, on what current or forthcoming trends might conceivably affect the accuracy of current projections in a manner comparable to that in which the unexpected low-price/moderate demand growth trend affected those of twenty years ago.

In our judgement, an obvious focus for such speculation is the long-run impact of information technology (IT) on the U.S. economy. Events of the first half of 2001 have dealt harshly with the more ambitious claims for the “new economy,” for example, the obsolescence of the business cycle. Indeed, very recent (summer 2001) revisions to the U. S. National Income and Product Accounts - specifically, lower estimates of economic and labor-productivity growth in the last half of the 1990s - have compelled at least a partial re-evaluation of more soundly-based but nonetheless optimistic conclusions regarding the long-run productivity-enhancing potential of IT (Oliner and Sichel 2000, Jorgenson and Stiroh 2000). Nevertheless, there is little doubt that the American economy is undergoing profound changes due to IT, that it has found its way at least partly out of the the productivity “doldrums” of the mid-1970s to the mid-1990s, and that the long-run macroeconomic implications, if not revolutionary, may be substantial.

A starting point for relating these facts to the subject of this paper is the mid-1990s debate, mentioned in the Introduction, over the potential long-run rate-of-decline of U. S. E/GDP . One school of thought in this debate is summarized by Kydes (1999), who argued that this rate was unlikely to exceed an annual average of 1.25% in the absence of substantial increases in energy (or, indirectly, carbon) prices. The late 1990s, however, saw an accelerated decline in the American E/GDP ratio. Following an average annual decline of 1.8% for the period 1973-96, and 0.8% from 1986 to 1996, E/GDP declined at an average annual rate of 2.9% from 1997 through 2000. Case study evidence has been put forth to suggest that diffusion and application of IT directly accounted for a possibly-substantial fraction of the shift (Romm 2000). By contrast, the milder-than-average weather in the late 1990s has been also suggested as the cause (Hakes 2000). A preliminary analysis indicates, however, that weather (along with fuel mix changes) accounted for only about half of the acceleration (Davis

et al. 2001). Overall, a detailed econometric examination at the micro level of potential links between the diffusion of IT and this shift in the aggregate trend remains to be undertaken.

However, some of the recent changes in the National Accounts related to information technology have been incorporated into the authoritative *Annual Energy Outlook* (AEO) series of the U. S. Energy Information Administration (EIA). The *AEO 2001* takes account of the upward revision in the historical rate of GDP growth due in particular to improved measurements of computer software investment. This revision also entails an increase in estimated underlying labor productivity growth. While the EIA has not adopted the view that IT has fundamentally changed macroeconomic trends, the changes in the *AEO* that result from incorporating these new estimates bear an interesting relationship to the topic of this paper.

These changes are summarized in Table 10. As the Table indicates, the key changes are the sizable upward revisions of GDP and labor productivity growth, and the E/GDP trend (in absolute value). The last line of the Table gives the results of applying our calibration method to both Reference Cases at a substitution elasticity of 0.4.³ Comparing with Tables 7 and 8, above, this calculation suggests that these revisions to the *AEO 2001* result in an underlying implicit autonomous trend that is much closer to the historical value than that in the previous year's *Outlook*. Insofar as many simulation models are calibrated to key aggregate trends in past *Outlooks*, this in turn indicates the importance of these models' taking account of at least the basic recent changes in the macroeconomy.

Table 10: Key trends in AEO 2000 and AEO 2001		
<i>Growth rates 2020 of:</i>	AEO 2000 Reference Case	AEO 2001 Reference Case
Energy consumption	1.1%	1.3%
Real GDP	2.2	3.0
Labor productivity	1.3	2.1
Primary average end-use energy price	0.5	0.7
Delivered energy intensity (1000 btu/1996 dollar)	-0.9	-1.5
Implied AEEI (to 2020) at $\sigma = 0.4$	-0.44	-1.18

Concluding Remarks

The results presented here are at least of historical interest. However, in our view they also demonstrate the utility of retrospectively examining the energy forecasting record for lessons to apply to current modeling efforts. Energy-economic simulation models of the kind considered here (in an earlier vintage)

³It is important to point out that the National Energy Modeling System (NEMS), which was used to make these projections, does *not* report an aggregate elasticity corresponding to the one defined in our simple calibration model.

have come to play a central if not predominant role in the analysis of policies to address global climate change. Although these models typically yield a wide range of abatement cost estimates even with standardized scenario input assumptions (Weyant 2000), the “central tendency” of such estimates tends to emerge as something of a consensus projection. We interpret our results as a reminder of sorts from history that this type of consensus should be viewed with rather more circumspection than is common.

While, as we have discussed, the simple calibration estimates here of the AEEI are only a starting point, statistically speaking, they do strongly suggest the need for renewed attention, in the context of large-scale simulation modeling, to the determinants of technological change. The energy literature of the late 1970s and early 1980s clearly reveals a focus on modeling the substitution possibilities that were demonstrated by the oil shocks. The research direction that leaders in the field advocated during this period - greater attention to disaggregate substitution elasticity estimates, and corresponding disaggregation in the modeling of energy production and consumption - has been for the most part followed. Current models include, on average, a considerable degree of sectoral disaggregation. But if, as is widely believed, success in cost-effectively mitigating climate change will depend substantially on future technological progress, then this particular type of detail, per se, is insufficient for modeling potential future policies. Better understanding the links among energy demand, energy prices, technological change, and other autonomous trends is of central importance as efforts continue to formulate national and international policies to address global climate change.

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Appendix

We first note that in our application of the model, we define R itself to be real GDP, with a price of 1 at every point in time. Now, at any time t , the first order condition for optimal allocation of E is

$$\frac{\partial Y}{\partial E} = a^{\frac{1}{\sigma}} \left(\frac{Y}{E} \right)^{\frac{1}{\sigma}} = P_E.$$

Solving this equation for E yields

$$E = Y a (P_E)^{-\sigma}.$$

Expanding Y from the budget constraint $Y = P_E E + GDP$, we can re-write the above equation for E as

$$E = \frac{GDP a (P_E)^{-\sigma}}{1 - P_E^{1-\sigma} a}.$$

Following Hogan and Manne, and using subscripts and sub-subscripts to index time, we can also solve for a_t , for any t , as

$$a_t = \frac{E_t}{Y_t} P_{E_t}^{\sigma}.$$

Thus, given 1) the value of a_{1982} (which is determined by the base year data); 2) the projected median values for GDP_{2000} , $P_{E_{2000}}$, and E_{2000} ; and 3) a value of σ , we can determine the value of a_{2000} , and therefore the average rate-of-change of a between 1982 and 2000, that calibrates the model. With this information, we can in turn determine the “autonomous” rate of change in $\frac{E}{GDP}$ that is implied by the calibration, as follows. Again re-arranging the first-order condition yields

$$\frac{E}{Y} = a (P_E)^{-\sigma},$$

so that

$$\frac{\partial \ln \left(\frac{E}{Y} \right)}{\partial t} = \frac{\dot{a}}{a},$$

or equivalently,

$$\frac{d \ln \left(\frac{E}{Y} \right)}{dt} = \frac{\dot{a}}{a}$$

where the derivative is taken holding P_E constant. The result is slightly different from the usually reported trend in $\frac{E}{GDP}$, but the difference is numerically negligible.

Our primary data source was the NEPP 83 Technical Report (USDOE 1983), which included a detailed comparison of the five sets of projections, including price and quantity data. This was supplemented by original documentation of several of the other (non-DOE) studies. To carry out the calibration, we followed as closely as possible the method for estimating prices used by the Energy Information Administration in its State Energy Price and Expenditure Report (USEIA2000b). This is based on estimates for the average price of primary energy to end-users across fuels. Because the information available from the studies was insufficient to exactly replicate the EIA method, we used the following approximation. Delivered primary energy price projections across fuels and sectors as well as sectoral consumption projections for each of the five studies are reported in NEPP 83, as are corresponding base year (1982) data. Because fuel prices for electric utilities were not reported, we used primary fuel prices as a proxy for these (i.e., refiner acquisition cost of oil, minemouth coal, and wellhead gas). These data allowed us to estimate the approximate average (sectoral consumption-weighted) price of primary energy implied in each study's year 2000 projection, and thus the projected increase from 1982 to 2000. The median projected increase across the studies was 39.5%, which was used in the calibration. For the "perfect hindsight" calibrations, we extrapolated the most recent EIA primary price average - from 1997 - to the year 2000 using a consumption-weighted index of delivered energy prices reported by the EIA for the year 2000. This yielded an increase of 20.3% from 1997 to 2000, for a 2000 value of \$5.57 dollars per million btu.